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BIOMASS ENERGY RECOVERY USING GASIFICATION AND CATALYTIC COMBUSTION TECHNOLOGY

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BIOMASS ENERGY RECOVERY USING GASIFICATION AND CATALYTIC COMBUSTION TECHNOLOGY

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November 1984

Prepared for

Montana Department of Natural Resources and Conservation
1520 East 6th Avenue, Helena, Montana 59620
Biomass Utilization and Cogeneration Program
Grant Agreement Number ED-LJW-650

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EXECUTIVE SUMMARY

Wood waste is a common form of biomass from which energy products such as heat, charcoal, gas, pyrolytic oil, etc. can be recovered. An investigation of feasible energy recovery systems is conducted, and an energy recovery system is proposed and evaluated for a specific lumber manufacturing application.

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INTRODUCTION

Conversion of biomass into alternative useable forms of energy (e.g. heat, charcoal, gas, pyrolytic oil, etc.) historically has involved a wide variety of processes. The thermal decomposition processes generally can be categorized as:

1) Direct Combustion - decomposition caused by complete burning (i.e., oxidation) yielding principally heat and ash.

2) Gasification - decomposition caused by partial burning under conditions of controlled temperature and limited oxygen, yielding principally a low Btu gas and some char and pyrolytic oil (tar).

3) Pyrolysis - decomposition caused by subjecting the biomass to heat, yielding principally a medium Btu gas, pyrolytic oil and char.

Numerous applications exist where a relatively small, cost effective system is needed that can accomplish this biomass energy conversion.

Specifically, a system is sought that can convert biomass into alternative useable forms of energy at a rate of at least 3-5 million Btu per hour. Higher outputs should be attainable by upscaling size or by interfacing multiple units, and lower energy outputs should be attainable by various turn-down or output storage alternatives to be discussed later.

SITE CHARACTERISTICS — GENERAL

Watters Lumber Co. is a lumber manufacturing firm located two miles northwest of Thompson Falls, Montana. Within the last several years the firm has made a successful transition from operating as a conventional sawmill to operating as a specialty mill. Conventional milling involves log breakdown into conventional framing lumber and boards. The specialty milling involves more band resaw, gang resaw and planer remanufacturing of cants and lumber into specialty paneling and siding patterns, furniture components, export (metric sized) and industrial items.

This transition has changed both (1) the energy requirements of operation and (2) the composition of the wood waste generated. Overall electrical energy consumption per thousand lineal feet of material processed has been reduced by using thinner kerf saws and by careful scheduling of machine facilities to lower peak power demand. Many of the new markets developed, however, prescribe that a larger proportion of the material be dried to more consistent and lower moisture contents. Thus, the need for a lumber drying facility exists. This transition also has resulted in the generation of wood waste containing a higher percentage of finer sawdust and shavings and having a much lower average moisture content than would be obtained from a conventional mill. Over the next several years, wood waste at the mill site is expected to average approximately 700 tons annually on a dry basis, thereafter increasing to an amount approximately 50% greater as new products are introduced.

Current disposal of this waste is by conventional combustion methods without the benefit of any energy recovery. The proposed system would provide for recovery of energy products and would greatly reduce undesirable environmental impacts inherent in current disposal methods.

EXISTING SYSTEMS FOR RECOVERING ENERGY FROM BIOMASS

Energy from biomass may be converted into useable forms (e.g., heat, charcoal, gas, pyrolytic oil, etc.) primarily through the thermochemical processes of direct combustion (i.e., complete oxidation [67,100]*), gasification (i.e., partial oxidation [18,39,53,84]), and/or pyrolysis (i.e., thermal decomposition in the absence of oxygen [84,88]). A large variety of systems exist, or are in various stages of research and development, for converting and recovering this energy. Those most feasible for the specific wood waste application being considered and their relative advantages and disadvantages, are now discussed.

DIRECT COMBUSTION OR INCINERATION

Fuel is introduced into the incineration chamber along with sufficient excess combustion air to ensure total combustion. Simple incineration yields no energy products other than heat. During start-up and as additional fuel is added, simple incinerators tend to generate substantial uncontrolled particulate emissions. Combustion temperatures often fluctuate widely and the systems are relatively unresponsive to matching varying load demands [14,41,67].

DOWNDRAFT (CO-CURRENT) FIXED BED GASIFIERS

These gasifiers allow both fuel and a limited supply of air to pass downward through a series of zones involving pyrolysis, oxidation and reduction, as indicated in Figure 1. This type of gasifier tends to generate relatively clean gas free of tar, has a good turn-down ratio (typically up to 5:1) and is useful where output demand is varying or intermittent.

Disadvantages of downdraft gasifiers include the need for extensive fuel preparation related to the requirement for low moisture content and uniformity of fuel size. Uniformity is necessary to prevent channeling of the oxidation zone. These gasifiers are not suitable for generating pyrolytic oils. They also are prone to slagging if the fuel contains over 5% inorganic material such as might be found in dirty bark [51,54,86,104].

* References appear in the bibliography.

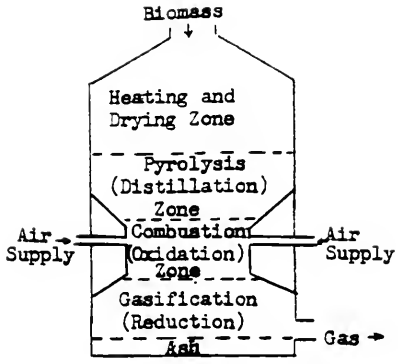


Figure 1. Downdraft Gasifier

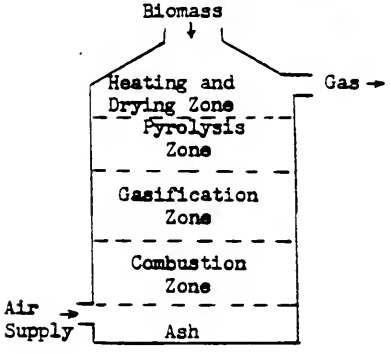


Figure 2. Updraft Gasifier

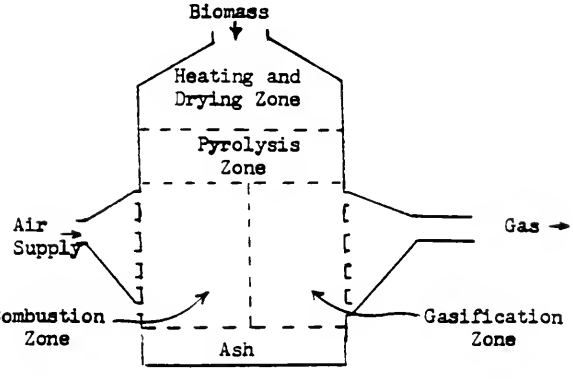


Figure 3. Crossdraft Gasifier

UPDRAFT (COUNTER-CURRENT) FIXED BED GASIFIERS

Fuel passes downward and a limited supply of air passes upward through the reaction zones as indicated in Figure 2. High moisture content fuels can be processed, with the rising gas exchanging heat and drying the descending fuel. The low temperature gas leaving the top of these gasifiers usually contains large quantities of tar and oil. If the gas is not closely coupled to a burner for immediate combustion, then extensive cleaning may be required to avoid excessive condensable tar buildup on system components [28,34,52,54,107].

CROSSDRAFT FIXED BED GASIFIERS

Fuel passes downward, air enters from one side of the reactor and gas exits from the other side as depicted in Figure 3. Crossdraft gasifiers have the advantages of rapid start-up time, responsiveness to varying load demands, and compactness of design [36,38].

Disadvantages of crossdraft gasifiers include high gas exit velocity and high temperature with a corresponding risk of burning out the unit and of encountering slag formation problems with high ash content fuels [54].

FLUIDIZED BEDS

Fuel is suspended in an upward flowing stream of air while undergoing reaction. These systems have a high throughput of fuel per unit area of reactor bed and therefore are relatively compact. They can be operated at low temperatures (down to 900°F) which favorably affects ash handling problems and refractory requirements. Fuel sizing requirements are less stringent than with fixed bed gasifiers. Fluidized bed reactors tend to have low turn-down ratios [18,46,50].

SUSPENSION BURNERS

Fine dry fuel particles are burned in a swirling or vortex-type suspension. Fuel preparation costs are high and fuel input controls elaborate [18,80]. Practical systems that have less stringent fuel preparation requirements need further testing and development [72].

PYROLYZERS

True pyrolyzers ensure that no oxygen comes in contact with the fuel when in the reaction zone, thereby precluding the occurrence of combustion or

gasification in the reactor [6,68]. Most commercial systems, however, allow varying amounts of oxygen into the reaction zone depending upon the output product desired and depending upon the extent to which internal heat generation is preferred for sustaining the energy conversion process.

One of the more common types of commercial pyrolyzers is the rotary drum kiln, often used for the production of charcoal [2,47]. It is a horizontal rotating cylindrical reactor into which wet or dry fuel is fed. Rotation maintains uniform control of the contact between the fuel and the heat source. Also, channeling is minimized. Residence time is accurately controlled by varying the rotational speed and angle of inclination of the reactor. Accordingly, the quality of the charcoal product is predictably uniform when entering fuel particles are uniform in size and moisture content. The rotary drum kiln can become a gasifier or a combustion unit by allowing limited or excess combustion air into the reaction chamber. Usually extensive refractory is required in the large commercial units and rotation of this large mass requires significant mechanical energy. Also indirect heating through the refractory takes a relatively long time to bring the fuel up to a pyrolyzing temperature.

Some other pyrolysis-type systems that have undergone extensive development include updraft configurations [16], crossdraft configurations [38], and gravitating bed configurations [59,88,103]. Much research is being conducted on rapid (i.e., entrained flow, fluidized bed, etc.) pyrolysis systems that show considerable promise for generating medium Btu gas, charcoal and/or pyrolytic oil [27,61,93].

CATALYTIC COMBUSTORS

The commercial use of catalytic devices to enhance the combustion efficiency of converting biomass to heat is a relatively new technology, although a similar approach has been used for some time in the auto industry to reduce pollutants for automobile emissions. It is important to distinguish between the concept of "catalytic combustion" as herein investigated and the concept of "catalytic reaction" which is an older technology pertaining to the mixing of catalysts (e.g., alkali carbonates or metallic oxides) into a reaction process for the purpose of altering the chemical composition of the output products [31,60,78,89]. "Catalytic combustion," on the other hand, shall herein denote the process in which combustion of the volatile gases, tars and oils found in "smoke" is enhanced by the use of a catalytic device that initiates or

accelerates the chemical combustion process, thereby effectively lowering ignition temperature [81,95].

One type of catalytic device is a ceramic honeycomb substrate having a surface embedded with one of the noble metals (usually platinum or palladium). The usual ignition temperature of wood smoke is in excess of 1000°F; however, a catalytic combustor can lower this ignition temperature to approximately 500°F [4,22].

The catalyst works as follows: At approximately 500°F, the hydrogen molecule, H_2, in the combustion gas breaks into hydrogen ions, H_1, some of which take up temporary residence in the catalytic layer. The other H_1 ions combine with oxygen to form H_2O. This oxidation process releases considerable heat and increases the temperature above the ignition temperature of the volatiles [94].

The system's design must be developed in accordance with a number of specific design objectives relating to simplicity, reliability, maintainability, versatility, safety, environmental acceptability, and cost effectiveness.

SIMPLICITY

Construction simplicity should ensure that the system be (1) compact, (2) modular (i.e., subsystems easily removable and multiple systems easily interfaced), and (3) potentially portable. Operational simplicity should ensure that the system (1) be easily started, (2) require minimum operator skill, and (3) be potentially suitable for automatic control.

RELIABILITY

System reliability is reflected by the dependability of subsystem components and operations, and the extent to which they properly connect and function with one another.

MAINTAINABILITY

The system should be designed to minimize problems from slag formation and corrosion, reduce the need for refractory or its frequency of replacement, and facilitate ash removal.

VERSATILITY

The system should have provisions for accommodating disparate characteristics of the available biomass resources, especially pertaining to differing biomass particle sizes and differing moisture contents.

The system should be responsive to varying energy-output demands, either by means of having an adequate turn-down ratio or by providing a means for storing excess energy outputs in some acceptable form.

Axiomatic to energy storage is the desirability of designing the system to produce multiple energy products of which at least some are storable, and preferably transportable. Furthermore it is desirable to be able to control and vary the relative proportion of each energy product generated. For example, if the system were being configured both to supply direct heat to a drying process

and to supply a low Btu gas to a cogeneration process, the proportion of direct heat and gas generated should be able to vary to match a varying proportion demanded by the two processes.

SAFETY

Unnecessary hazards that may cause risk to operating personnel must be eliminated. Risks of gas explosion, fuel dust explosion and exposure to carbon monoxide poisoning are of particular importance.

ENVIRONMENTAL ACCEPTABILITY

Ecologically disruptive characteristics of particulate and liquid effluents emanating from the system must be monitored, minimized and controlled within acceptable limits.

COST EFFECTIVENESS

Every effort must be made to obtain a design that minimizes capital costs, operating costs and maintenance costs. Furthermore, for any given level of financial commitment it is desirable to maximize the energy conversion efficiency within the constraints of the resources available. Energy generated by the system must be cost competitive with the other sources of energy it is designed to replace. The system must have attractive investment recovery potential, with an expected payback period of less than three years. The system should provide sufficient energy to dry up to 5 million board feet of lumber annually.

RECOMMENDATIONS FOR ATTAINING DESIGN OBJECTIVES

General approaches and recommendations for attaining design objectives are as follows.

SIMPLICITY DESIGN RECOMMENDATIONS

Construction simplicity can be enhanced by close coupling the processes and corresponding hardware. The sizing of all components should be engineered carefully, and they should be readily accessible for maintenance or removal. Construction materials should not be excessively heavy. Massive refractory will be minimized and instead double-walled heat-exchange type construction will be used wherever possible to moderate heat flux. Critical components may need to be lightweight, high temperature steels. If possible, subsystems should be detachable to work in a "stand alone" mode. Fuel and air inputs and product outputs should be arranged to accommodate connection of multiple units, and individual units should be skid mounted for transportability.

Operational simplicity suggests that overly elaborate or complicated start-up and control procedures should be avoided to preclude the need for extensive decision making by the operator. Operator skill requirements should be reduced by pre-identifying critical control parameters and predetermining the appropriate control points in order that simple "yes-no" or "go-no go" decisions can be made. Relationships need to be established between "subjective" process characteristics (e.g., visible smoke discharge from the stack) and specifically measurable process characteristics that can be monitored with controller-type instruments (e.g., temperature in the secondary combustion chamber monitored with a thermocouple and air flow into the chamber monitored with an anomemeter). These relationships, if properly established and instrumented, can provide the basis for automatic control.

RELIABILITY DESIGN RECOMMENDATIONS

Good process and equipment monitoring and good predictive and responsive process control in subsystem components and operations is necessary to achieve overall system reliability. For example, one of the primary areas of potential unreliability is in the fuel handling subsystem. Biomass tends to be susceptible to bridging and clogging. In order to ensure continuous movement of the material throughout the system, flow restrictions need to be kept to a minimum

and suitably sized augers, agitators or rams need to be integrated into the system.

MAINTAINABILITY DESIGN RECOMMENDATIONS

In order to minimize slagging problems, operating temperatures in areas of high ash buildup will be kept below 1800°-2000°F. Also, it is desirable to minimize the use of fuel containing high mineral content material such as dirt . Provisions will be made for easy removal and cleaning of components that may be subjected to slag formation.

Corrosion problems can be reduced by using resistant materials such as stainless steel and ceramics. Also, potentially corrosive condensibles will be kept above condensation temperatures as they pass through components susceptible to corrosion.

Limiting extensive use of refractory can help reduce maintenance problems, as refractory replacement and upkeep can be quite expensive. If surface temperatures of combustion chambers can be controlled and maintained at sufficiently low levels, refractory use might be reduced. When refractory must be used, thermal shock might be minimized by avoiding wide fluctuations in operating temperatures. For example, surface spalling may occur on refractory allowed to get completely cold under intermittent operation. Also, physical shock should be minimized by introducing fuel into a combustion chamber uniformly and without jarring or impact.

Provisions should be made for periodic removal of ash, such as with an automatically activated or timed auger, without interrupting the system's operation.

VERSATILITY DESIGN RECOMMENDATIONS

The system should be able to accommodate a diversity of fuel sizes and moisture contents without requiring elaborate or expensive fuel preparation processes. Specifically, the system should be able to deal with dry or green sawdust, shavings, bark and, if possible, small wood chunks. Insofar as possible, provisions will be made to enable at least partial fuel drying in the fuel infeed system.

As momentary (say, less than hourly) energy-output demands change, the system should be able to respond to these changing demands through timely adjustment of the control parameters (e.g., fuel infeed rate, draft, etc.). For

example, in a lumber drying process a desirable turn-down ratio for a system generating heat going into a single drying area would be at least 5:1. That size turn-down ratio would be unnecessary if excess heat could be diverted among multiple drying areas.

The need for a high turn-down ratio also might be reduced by finding ways to store and/or transport some portion of energy output in excess of momentary demand. Neither heat nor low Btu gas is readily storable, though it could be diverted to a subsystem that drys high moisture biomass which in turn might be stored, thus effecting an indirect storage of the excess energy.

A transportable, though not readily storable form of energy output could be obtained by generating electricity from the heat (via a steam turbine driving a generator) or from the low Btu gas (via an internal combustion engine or gas turbine driving a generator). It might be even more advantageous to produce potentially profitable forms of energy output that are both storable and transportable. Two candidates to be considered are pyrolytic oil and charcoal. Versatility of the system would be considerably enhanced if one or more of these products, along with heat and low Btu gas can be generated. To control the relative proportion of each form of energy output the design must be able to provide for carefully controlled temperatures, heating rates, and gas residence times in the high temperature regions of the reactor.

SAFETY DESIGN RECOMMENDATIONS

Pressure relief valves and rupture disks will be placed on closed vessels that are subject to conditions that might result in an explosion. Whenever gas is to be ignited and burned, normal interlocks and sensing devices will be provided for flame failure protection. If the flame cannot be ignited nor sustained at the intended point of use, the gas shall be diverted to a flare stack.

The risk of carbon monoxide emissions from the system is substantially reduced if it is operated at a slightly negative pressure. This will be done by using induced draft rather than forced draft systems. Also carbon monoxide and phenol detectors and alarms are recommended to protect personnel in closed working areas.

ENVIRONMENTAL DESIGN RECOMMENDATIONS

Particulate emissions will be minimized by incorporating accurate monitors and controls into the system to ensure that proper

combustion/gasification/pyrolysis conditions are maintained during operation. A portion of the low Btu gas and preheated secondary combustion air will be combined in an afterburner-type operation to prevent unburned particulate from escaping the reactor. During system start-up and when fluctuating temperatures fall below desired operating levels, catalytic combustors will augment combustion in the afterburner.

The generation of corrosive and toxic condensible liquids must be controlled to prevent adverse environmental impact. Process temperatures can be kept high enough to avoid undesirable condensates from forming before the low Btu gas in which they are entrained can be burned. Total volume of these liquids (which also include water), can be reduced by predrying the biomass before processing it. It is desirable to reclaim the pyrolytic oil contained in these liquids for use or sale as fuel.

COST EFFECTIVENESS RECOMMENDATIONS

Favorable system cost effectiveness requires that the system attain high output efficiencies at acceptably low cost. These output efficiencies will be achieved by (1) extensive use of double-wall construction and heat exchange surfaces to minimize unrecoverable heat losses, (2) using flue gas to assist in pre-drying incoming fuel, (3) employing catalytic combustors and a gasification afterburner in the portion of the system generating process heat to ensure complete combustion of all volatiles and particulate, and (4) employing appropriate filtering, condensing and other recovery subsystems in portions of the system generating pyrolytic oil and charcoal.

Initial construction costs will be reduced wherever possible by using simplified designs and readily obtainable standardized industrial components or components easily fabricated. Operating costs will be reduced by automating as many monitoring and control functions as possible. Maintenance costs will be kept low by careful selection of the critical construction materials and components that need to be corrosion resistant and tolerant of high temperatures.

From an investment point of view, the system must produce the desired energy outputs at a competitively low cost, ensuring a short payback period and high internal rate of return on investment capital.

The assessment of alternative system designs involves the identification of technically and financially feasible alternatives most likely to be able to convert the widest variety of available fuel types into the widest variety of desired energy output products. For example, the ideal system for the typical sawmill would convert (without additional fuel preparation) wet and dry sawdust, shavings, bark, chips, trim ends, edgings and large chunks into heat, gas, oil, charcoal and electricity. Such a system is not currently attainable within the constraints of technical and financial feasibility, so numerous compromises must be made to arrive at a final acceptable selection.

DESIGN ALTERNATIVES - FUEL CONSIDERATIONS

Fuel Moisture Content and Size Uniformity

Systems that can function well on non-uniform fuel sizes and moisture contents tend to operate by direct combustion. When direct combustion systems are able to operate on large green chunks and high moisture content fuels, then extensive fuel preparation costs associated with hogging, chipping, and/or drying may be avoided. Often however, wide fluctuations in the combustion bed temperature may occur as fuels with disparate size and moisture content characteristics are introduced into the combustion chamber. Such depressed temperatures encourage the formation and emission of undesirable unburned particulates. Proper and complete combustion should be attainable by the use of an afterburner supplemented by the use of a catalytic combustor.

Firms that already have incurred the large fixed cost of buying and installing hogging, chipping and/or drying equipment no doubt economically could justify continuing to uniformly size all of their fuel for ease in handling.

Fuel Drying

Although minimal fuel preparation was one of the design recommendations made in a previous section, it should be noted that some drying capability may be desired, especially on fuel such as sawdust and shavings that can be efficiently dried. The efficiency of biomass energy conversion is markedly improved by the use of dry fuel [12]. Also, the Btu content of the gas generated in a gasifier or pyrolyzer is quite sensitive to the

moisture content of the incoming fuel [54,p.109]. Therefore, simple drying capability will be assessed for possible inclusion in the final design.

DESIGN ALTERNATIVES - ENERGY OUTPUT PRODUCT CONSIDERATIONS

A system is preferred that could produce the most versatile combination of energy output products, such as heat, gas, charcoal, oil and electricity.

Heat

One of the primary energy output products desired from the system is clean direct process heat, which can readily be used for drying and space heating purposes. All prevously described combustion, gasification and pyrolysis systems can generate heat directly or indirectly (by burning output products) with varying degrees of efficiency and cleanliness.

Direct combustion systems have been the principal sources of direct heat. Any selection of such a system would require careful consideration of heat control and potential emission problems.

Gas

Gasifiers can be used to generate low Btu (90-180 Btu/scf) gas and pyrolyzers can be used to generate medium Btu (300-550 Btu/scf) gas[93]. Such gas can be transported through pipes to burners for heating and drying purposes, and when properly conditioned can be used to fire internal combustion engines or gas turbines. Especially in the case of low Btu gas, close coupling the system to the point of use is preferred in order to minimize the possible buildup of char and tar in the transmission pipes. Such gas also could be used for controlling other combustion processes as in a secondary combustion chamber to ensure complete combustion.

The cleanest (tar free) gases are usually obtained from downdraft gasifiers [84,p.III-15] and crossdraft gasifiers [54,p.73]. Inclined grate gasifiers approximate the gasification characteristics of crossdraft gasifiers and have proved to work well on fuels that are relatively uniformly sized [37]. Efficiencies and gas heating values (Btu content) of all gasifiers and pyrolyzers are significantly increased when the fuel is dry.

Charcoal

Charcoal is readily produced in pyrolyzers [2,6,16,21,69]. Markets exist

for it at briquetting plants, although the cost to transport it to the plants often is a substantial portion of its total value for such use. More lucrative markets exist for activated charcoal [47] although the process to activate charcoal involves elaborate high temperature (over 1300° F) steam equipment and is quite costly [69]. Charcoal could be a useful product for on-site energy storage because its heat content typically exceeds that of dry wood by more than 50% by weight [54,p.104]. If charcoal is produced, quenching and fire-safe storage would need to be included.

Oil

Pyrolytic oil has the same general characteristics as No. 6 fuel oil with significantly less sulfur content [25]. Heat content of the oil is approximately 10,000 BTU per pound which is about 60% of the heating value of No. 6 fuel oil [35]. Production of this product, high in phenolic compounds and containing toxic water-soluble tar, would require precaution to protect health and the environment. Like charcoal, it could be a useful product for on-site energy storage and possibly markets could be developed that would supplant the use of petroleum based fuel oil.

High oil yield processes (say, over 20% by weight) often employ rather elaborate flash pyrolysis techniques in fluidized bed systems [64] although good oil yields have been obtained from updraft pyrolyzers such as the system developed at Georgia Institute of Technology [16].

Electricity

Electricity is a useful energy output product in almost any industrial environment. It can be produced indirectly from any of the previously discussed biomass energy output products, using the heat to operate steam power generation systems [98], Stirling engine/generator systems [93], Rankine engine/generator systems [8], or using the gas to fire internal combustion engines [70] or gas turbines [66] that drive electrical generators.

In remote locations not accessible to conventional electrical power utilities, the generation of on-site electrical power may require a choice between generating from biomass resources or generating from, say, fossil fuel sources (e.g., a diesel engine/generator system). Such circumstances may favor the biomass system. On the other hand, when electrical requirements are small (e.g., around 300 kw or less) and when electricity can be bought from a power

utility for 4¢-6¢ per kwh, on-site electrical generation is untenable [48]. The cost to establish on-site electrical power generation capability, even for such small requirements, appears to be far too large (over $500,000) [1,48] to justify making this investment. Even much larger (say, up to 1 megawatt size) cogeneration systems that can sell excess electricity to utilities still appear financially questionable, particularly until the equivocal "avoided cost" price at which utilities will buy electricity becomes resolved [101]. For these reasons, on-site electrical generation will not be significant in our assessment of design alternatives.

Some conventional lumber manufacturing firms might generate all of the various fuel types (i.e., wet and dry sawdust, shavings, bark, chips, trim ends, edgings and chunks) in sufficient quantities to justify a complete configuration of biomass conversion equipment capable of generating all of the previously discussed energy output products. The process flow schematic of this general system is depicted in Figure 4.

The proposed equipment in the schematic would process the various types of fuel inputs (solid lines in the schematic) and generate the energy output products (broken lines in the schematic). The system would accept fuel of like type, segregated for diversion to the conversion equipment best suited for each fuel type. For example, chunk type materials, oversized and/or undersized material, bark, and wet material might go to the combustion chamber for conversion into heat by means of direct incineration. Dry shavings and chips might go to the gasifier for conversion into low Btu gas, pyrolytic oil and heat. Dry sawdust might go to the pyrolyzer for conversion to medium Btu gas, charcoal and pyrolytic oil. A proposed catalytic combustor is designed into the process to act as an afterburner for both the gasifier and the combustion chamber as needed, and can be circumvented when desired. The gasifier also can be used as an afterburner, underfire, or overfire for the combustion chamber. Gaseous output products from the gasifier and/or the pyrolyzer can be cleaned in condensers (or demisters). Note that heat must be divertable to the pyrolyzer from the gasifier and/or the combustion chamber in order to sustain pyrolysis (an endothermic process). Heat also is available to the fuel dryers. Overall system thermal efficiency is enhanced if most or all of the fuel drying can be accomplished by the flue gas before it exits to the stack.

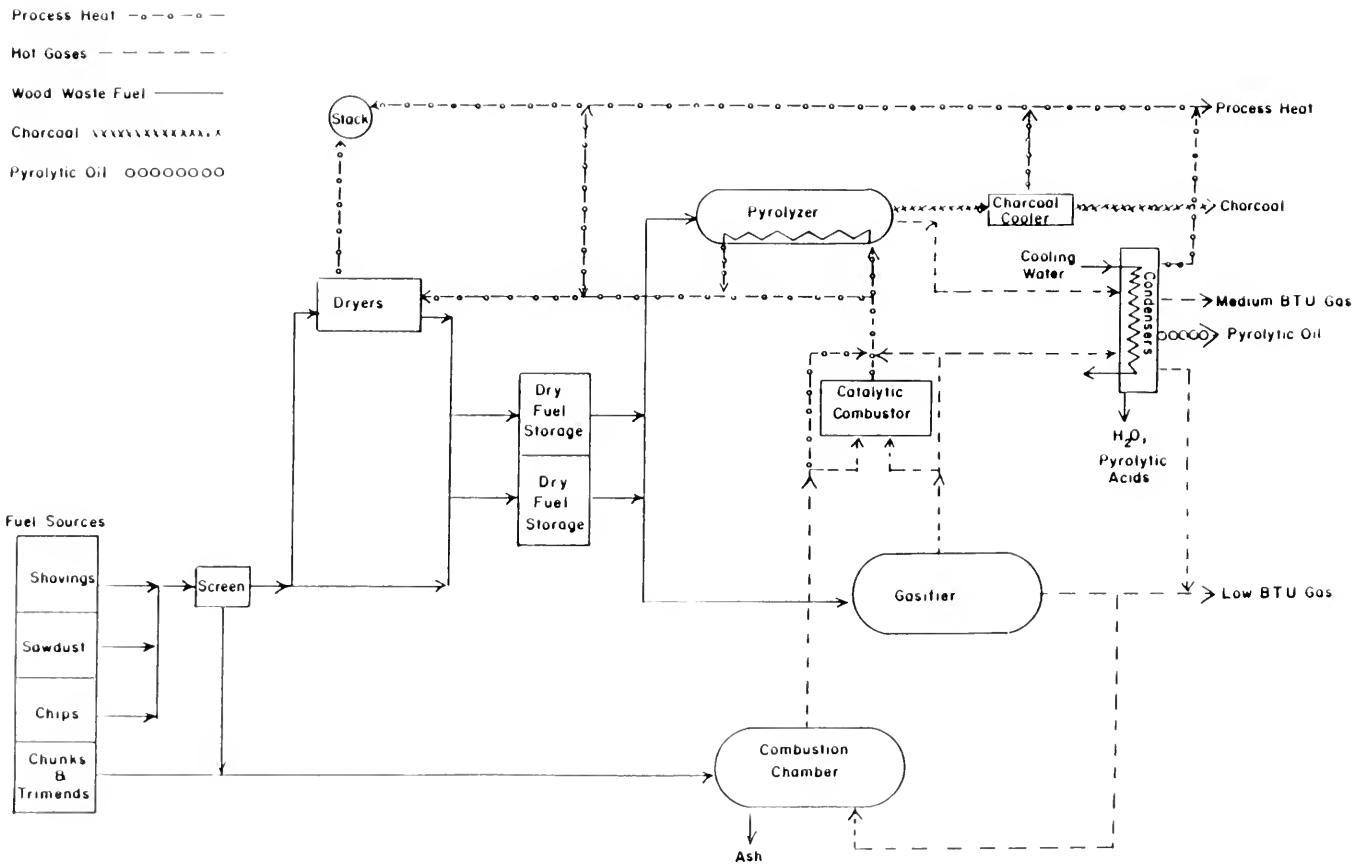


Figure 4. Process Schematic For Waste Wood Gasification System

GENERAL SYSTEM EQUIPMENT

The general equipment configuration would meet design objectives for a larger mill that has significant quantities of each fuel type discussed, including heat, gas, oil, and charcoal. A site specific design will be presented in a later section that is based on the more limited fuel types and quantities actually available at the site for generating principal energy output products of heat and gas.

For the general system, it would be advantageous to have all of the main processes (i.e., drying, combusting, gasifying and pyrolyzing) consolidated into a single compact unit, such as is conceptualized in Figure 5.

DRYER SUBSYSTEM

A "shuffleboard" type live bottom unloading device [19] might be adapted to move wet fuel (sawdust or shavings) through a multi-level drying chamber. If the fuel is to go directly into one of the combustion, gasification or pyrolysis subsystems, the material could come in direct contact with hot flue gas. If it is to be transferred to storage after drying, heat exchange by conduction through the floor of each level of the drying unit should be used to avoid a fire hazard in the storage area.

Rotating pipes, similar to but smaller than rotary drum dryers, also might be used for indirect drying. These could be situated in the upper portion of the combustion chamber.

COMBUSTION SUBSYSTEM

A double-walled refractory-bottomed combustion chamber should be used, with a slide or moving grate to enable loading of trim ends, edgings and other chunks. The chamber should have preheated underfire and/or overfire primary combustion air, preheated secondary combustion air, and bypassable catalytic combustors in the flue to ensure complete combustion. A star valve under the final combustion zone would periodically purge ash into an ash auger.

GASIFER SUBSYSTEM

An inclined pinhole grate [70,p.IV-8] can be used in a configuration similar to a crossdraft gasifier. Experimental tilting of the grate should establish the angle that most nearly parallels the fuel's angle of repose.

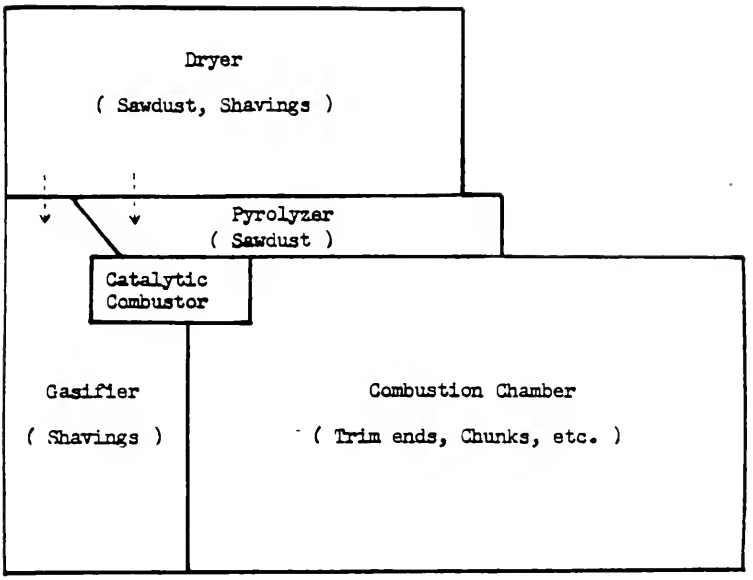


Figure 5. Conceptual Equipment Configuration

Moisture content and size uniformity make shavings or chips the best fuel candidate for this subsystem, although sawdust or screened bark might be used successfully if proper fuel bed uniformity is maintained. Knife gates and leveling augers control the fuel level. Primary combustion air goes through the pinhole grate as a result of low negative pressure in the gasification chamber caused by an induced draft system. Ashes drop into the same ash auger that cleans the combustion chamber, with the star valve preventing blowback between the two chambers.

PYROLYZER SUBSYSTEM

Pipes heated by and rotating in the upper portion of the combustion chamber might be used as small pyrolyzer tubes. Each tube would be a scaled-down version of a rotary kiln [68]. Residence time of the fuel going through the tubes is regulated by the rotation rate and the tube's angle of inclination. Reaction temperatures could be increased further by burning additional gas (either from the gasifier or the pyrolyzer) around the outside of the tubes, thereby influencing the relative proportions of gas, charcoal, and pyrolytic oils being produced. Experimental results using a calciner tube 6" diameter by 11' long [6] and using a rotating tube furnace [61,p.410] indicate this approach is feasible. Fuel in the pyrolyzer should be dry.

The proposed integrated system comprised of these subsystems appears in Figure 6.

INTEGRATED SYSTEM

The integrated system depicted in Figure 6 combines all functions previously described. The coarse residue (chunks, trim ends, edgings, wet bark, etc.) is injected into the combustion chamber with a simple moving grate system comprised of narrow steel plates that simultaneously and jointly move forward toward the combustion chamber, and sequentially and alternately (i.e., non-adjacent plates) move backward. Long hydraulic rams have been used to perform this injection in other combustion systems [58]; however, the moving grate system should be much more compact.

Whenever the variable conditions in the combustion chamber become unsuitable for clean, complete combustion (e.g., when a fresh charge of fuel is injected into the combustion chamber or when high moisture content fuel temporarily lowers temperatures), then unburned volatiles and smoke leaving the

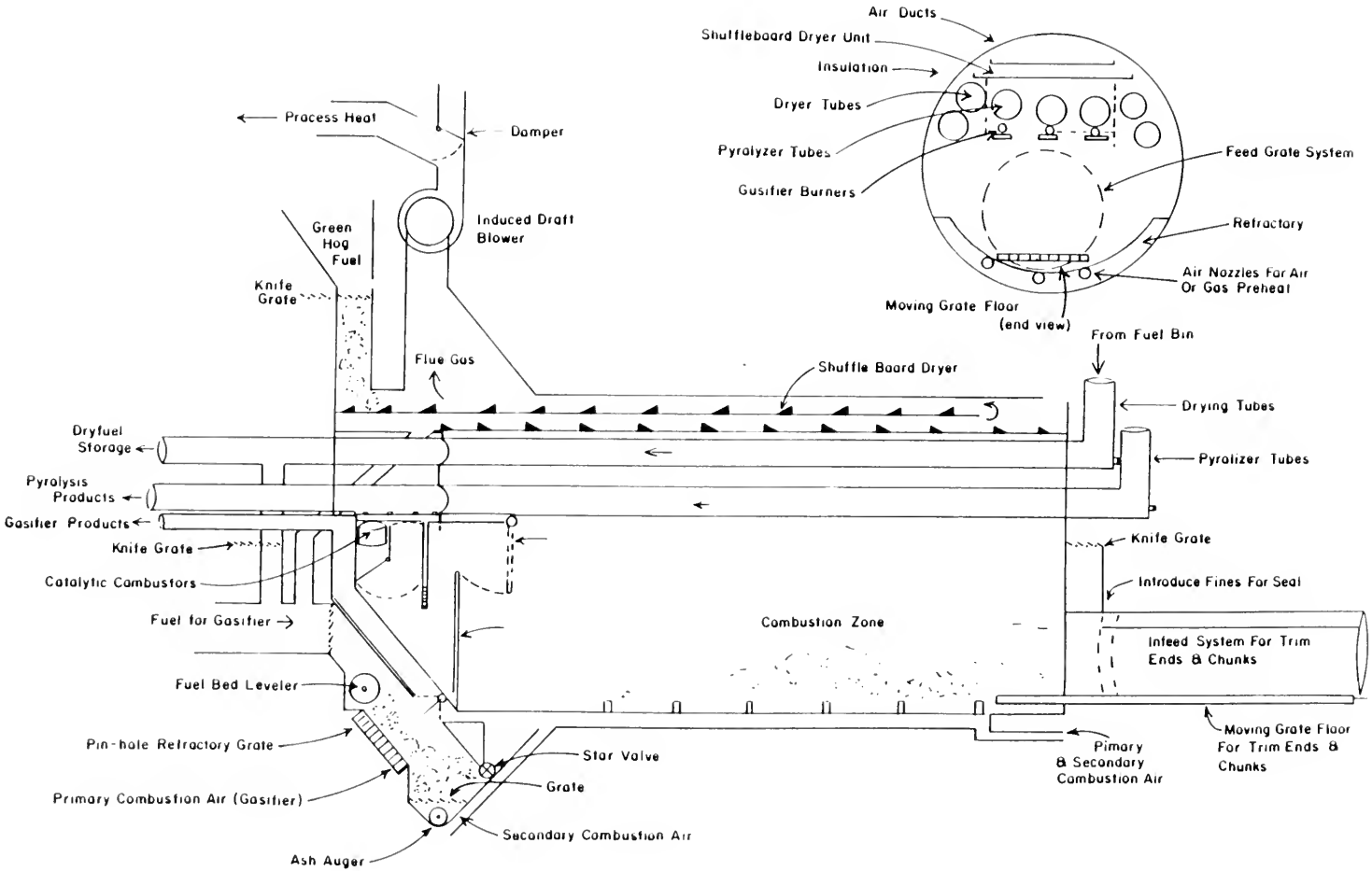


Figure 6. Integrated Waste Wood Gasification System

combustion chamber are diverted through catalytic combustors. A more detailed discussion is presented in Appendix A of how the catalytic combustors should be engineered for combustion effectiveness.

Dry shavings are fed onto the top of the inclined pinhole grate of the gasifier. The gas generated can be directed to (1) control combustion (underfire or overfire) in the combustion chamber, (2) act as an afterburner in the flue above the combustion chamber, (3) control heating on the final pyrolyzing zone of the pyrolyzer tubes, (4) provide heat for the fuel drying subsystem, and (5) exit the system through an insulated pipe to remote burners used for process heat purposes.

Dry sawdust is fed into the rotating pyrolyzer tubes, with temperature monitors controlling the feed rate, rate of tube rotation, and heat flux provided by the combustion chamber and gasifier.

Fuel to be dried is fed into the shuffleboard drying subsystem and/or fuel drying tubes. Material flow rates and temperatures regulate the drying rate. Flue gas does most of the drying, and can partially or completely bypass the drying subsystem if temperatures become too high. Flue gas does not come into direct contact with fuel in the dryer tubes, so this fuel can be stored after drying with no risk of fire.

Process parameters for operational control include temperatures, volumes, and other physical characteristics associated with the processes of combustion (conventional and catalytic), gasification, pyrolysis, condensation (or avoidance of condensation), fuel sizing, fuel drying, process heat demand, and stack discharge.

CONVENTIONAL COMBUSTION PARAMETERS

Temperatures in the combustion zone need to be maintained below 1800°F to minimize heavy refractory requirements and slag formation. Metal surfaces unprotected by refractory and exposed to combustion zone temperatures need to be maintained at acceptable operating temperatures by cooling from the back side of these surfaces with air flows. Because the heat transfer rate of combustion or flue gas to the metal (on one side) is approximately equal to the heat transfer rate of air to the metal (on the other side), the metal temperature is approximately equal to the average of these two temperatures [17,p.24]. Most non-stainless steel components require this average temperature to be less than 1000° F for continual operation without sustaining damage. Various stainless steels permit this average to be as high as 1900° F, and many ceramic structures perform well at temperatures in excess of 2000° F. Air flow cooling must be increased on these exposed surfaces or combustion zone temperature must be decreased when this average temperature exceeds the acceptable level. The air warmed in this exchange of heat should be used as primary and secondary combustion air and for process heat. These temperatures should range up to 500° F.

The volume of air flow into the combustion zone must be sufficient to ensure the desired level of combustion but not so much as to inordinately lower combustion temperature nor create high velocity entrainment of ash and unburned char in the outgoing flue gas. Provisions should be made in the design for air flow volumes into the primary combustion chamber to exceed stoichiometric levels (i.e., sufficient to result in complete combustion of the fuel) although under usual operating conditions such air flow will be less than stoichiometric, with complete combustion taking place in the secondary

combustion chamber (if desired). It is in the secondary combustion chamber where most of the combustion control takes place using the preheated secondary combustion air, afterburners from the gasification process, and catalytic combustors. Average air flow into the primary and secondary combustion chambers combined would be expected to provide approximately 10% - 50% excess air. The source of this air should be from the heat exchange surfaces and from the induced draft system.

CATALYTIC COMBUSTION PARAMETERS

When temperatures in the combustion zone drop below approximately 1000° F, many of the volatile gases and hydrocarbons in conventional combustion systems do not ignite, and pass through the system as unburned "smoke." A catalytic combustor may be used to ignite these gases and hydrocarbons at temperatures as low as 500°F with its effectiveness increasing with increasing temperatures up to approximately 1000° F. A catalytic combustor operates most efficently when the temperature of secondary combustion air and the gas going into the combustor is 700° - 1000° F [4]. At temperatures over 1000° F and with proper proportions and mixing of secondary combustion air with flue gas, complete combustion should be sustainable without assistance from the catalytic combustor [100]. At such times, a bypass can be used to vent the flue gas around the catalytic combustor. This bypass is also useful for reducing the pressure drop that would otherwise be incurred if the gas were forced (by induced draft) through the catalytic combustor.

Pressure drop, or resistance to draft, is an important consideration in the selection of cell density and size of a catalytic combustor. In commercially available catalytic combustors, the higher cell densities (say, 25 cells per square inch or more) and longer lengths (say, over 3" long) increase the catalytic surface area and performance but are more susceptible to plugging and increase the resistance to draft. Data on catalytic combustors available from Corning Glass Work's three inch long by 5.66 inch diameter 16 cell per square inch catalytic combustors states that it will accommodate five cubic feet of firebox volume, and causes a draft resistance of .0018 psi (.05 inches of water) at approximately 90 scfm air flow [22].

GASIFICATION PARAMETERS

Temperatures in the gasification zone influence the relative proportions of

gas (and its heat content), oils and char obtained from biomass undergoing gasification. Control of these proportions generally occur in the temperature range of 900° - 1400° F. Tars and oils usually crack into gaseous form at approximately 1100° -1200° F [55].

An air volume of approximately 15% - 30% of stoichiometric is needed to sustain a gasification process primarily producing a low Btu gas [52]. This volume should be provided primarily by an induced draft system operating under slightly negative pressure, supplemented with some preheated air coming in from the heat exchange surfaces.

PYROLYSIS PARAMETERS

Initial thermal decomposition of biomass under pyrolytic conditions (i.e., indirectly heated in the absence of oxygen) begins at tempratures under 300° F, and as the temperature is raised to approximately 800° F, volatile gases commence to be driven from the biomass. Accordingly, control temperatures for the pyrolysis process need to be maintained in the range of 600° - 900° F, as proportions of product output can be influenced through control of this parameter [55]. Once the biomass in the pyrolysis unit has reached the desired temperature, its residence time at this temperature is expected to be less than 10 minutes. If pyrolytic oil is desired, residence time of the volatile vapors carrying this oil should be kept short, preferably well under one minute [84].

CONDENSATION PARAMETERS

As the temperature of the volatiles in the gas stream drop, pyrolytic oils and other uncracked distillates can be condensed. This condensation commences at around 750° F and is nearly complete, with the exception of water, by 250° F [54,p.47]. It generally is desirable to maintain operating temperatures above 220° F in order to avoid generating sizeable quantities of highly corrosive water-borne pyrolytic acids.

FUEL SIZING AND DRYING PARAMETERS

It is anticipated that for most of the intended uses of the proposed system fuel drying would be conducted only on wood waste from those production activities that generate suitably sized material ready for the gasification and pyrolysis processes. This sized material includes predominantly sawdust, shavings, chips, and screened (under 2") bark. Although chippers, shredders, pelletizers,

etc. can be used for fuel size reduction and densification, the costs (fixed plus operating and maintenance) likely would exceed $6-$10 per dry ton in most new installations, and undoubtedly these costs will continue to increase [12;70,p.III-4]. For this reason, fuel segregation (i.e., diverting the appropriately sized fuel to its best final use) will be favored over fuel reduction. Admittedly, constraints imposed by some types of biomass generating processes, fuel handling equipment, storage limitations, etc. may compromise the desired goal to avoid fuel reduction.

Temperature of the heat going into the drying process should be maintained at approximately 400° - 600° F on fuel intended to be stored (to avoid initiating premature combustion), and the drying temperature may rise well above 600° F on fuel intended to be used immediately. Temperature of the exhaust from this drying process will be influenced by the initial moisture content of the wood waste being dried and by the residence time in the dryer. Residence times and temperatures should be sufficient to lower the average fuel moisture content to less than 20% (oven dry basis).

Theoretical heat necessary to evaporate moisture from fuel is approximately 1000 Btu per pound of water removed; however, due to generally unavoidable thermal losses, actual requirements for a relatively efficient dryer will be closer to 1500 Btu per pound of water removed [76,p.23]. For example, if incoming fuel needed to be dried from 65% to 15% moisture content, then each pound (dry basis) of incoming fuel would need to lose one pound of water, requiring approximately an additional 1500 Btu of heat for this drying.

The recoverable heat and the combustion efficiency as a function of fuel moisture content for conventional combustion processes have been estimated by Bliss and Black [12]. Using their assumptions of bone dry wood with maximum heating content of 8600 Btu per pound, initial wood and air temperature of 62° F, flue gas exit temperature of 450° F and 50% excess of stoichiometric air, then for wood with a 15% moisture content the estimated recoverable heat is approximately 6900 Btu per pound and combustion efficiency is approximately 80%. These same assumptions for wood with a 65% moisture content result in an estimated recoverable heat of approximately 4800 Btu per pound and combustion efficiency of approximately 55%. Thus such a system designed to generate a sustained net heat output of at least 5 million Btu per hour (excluding drying) and operating only on 15% moisture content fuel would need at least 5,000,000/6900 = 725 pounds of fuel per hour. For 65% moisture content fuel and

attendant drying requirements, estimated fuel needed to generate 5 million Btu net recoverable heat would need to be at least 5,000,000/4800 = 1040 pounds of fuel per hour.

PROCESS HEAT PARAMETERS

If desired, direct use of process heat from the system can be made at temperatures in excess of 2000° F (e.g., by direct combustion of the gas, pyrolytic oil and/or charcoal). The process heat entering direct-fired lumber or veneer drying facilities often can be mixed with recycled kiln air to ensure that the re-entering mix is reduced to under 600° F. Temperatures throughout the kiln typically are maintained under 250° F (dry-bulb temperature).

STACK DISCHARGE PARAMETERS

Heat loss from the stack must be kept sufficiently low to ensure system efficiency and maximum recovery of useable heat. However, stack temperature generally will be kept well above 220° F to avoid formation of undesirable condensibles in the stack and to assist the induced draft system.

Particulate discharge will be minimized by careful control of the combustion process parameters.

DESIGN EVALUATION — TECHNICAL AND ECONOMIC CONSIDERATIONS

The evaluation of a site-dependent system must recognize the constraints of actual fuel types existing and expected to be available at the site, and actual energy output products that feasibly can be obtained at that site.

Wood waste available at the site over the next two years is expected to be approximately 700 tons (dry equivalent) annually and rising thereafter to approximately 1100 tons annually. Details of these estimates are presented in Appendix B. The conversion of the quantities in Appendix B to their equivalent net Btu content, after adjusting for that portion of their energy content diminished due to moisture content, is presented in Appendix C. This annual net available energy is approximately 10,000 million Btu for two years and rising thereafter to aproximately 18,000 million Btu.

The quantity of process heat required to dry lumber in a conventional dry kiln (including typical heat losses) is approximately 2500 Btu per pound of water removed [76]. A specially designed dry kiln at the site will contain considerable insulation plus air-flow recycling through heat exchangers and condensers to recapture a large proportion of the removed moisture's latent heat of vaporization. That is, most moisture removal will take place in the form of condensed water rather than by venting hot moist air. The drying efficiency of this particular kiln is expected to reduce heat requirements to under 1500 Btu per pound of water removed. The average amount of water to be removed from the various softwood products at the site is approximately 1.2 pounds of water per board foot, so the average estimated heat requirement is 1500x1.2 = 1800 Btu per board foot.

The minimum acceptable energy output at the site must be sufficient to dry at least 2 million board feet per year initially (i.e., 2 millionx1800 = 3600 million Btu) and at least 5 million board feet per year within three years (i.e., 5 millionx1800 = 9000 million Btu). The preferred kiln operating capacity should allow for expansion to at least 30%-40% more than this minimum. Also, the system may need to provide some additional heat for supplemental fuel drying prior to fuel storage. Therefore the preferred energy output capacity should be approximately 5000 million Btu per year initially and rising to 12,000 million Btu per year within three years.

If the kiln were to average, say, two 48-hour charges per week (i.e., 2x48x52 = 4992 operating hours per year), then the average heat demand per

hour would eventually need to be 12,000 million/4992 = 2.4 million Btu per hour. In a conventional kiln it usually is necessary to design for a peak heat demand that is at least 50% greater than average heat demand in order to facilitate rapid initial heat-up of the kiln charge. This oversizing is largely unnecessary for the proposed on-site kiln because it will be comprised of multiple smaller drying chambers for which the initial heat-up of the charge in each chamber will be scheduled to avoid such large peak heat demands. A design size for the system of 2.5-3 million Btu per hour with a turndown ratio of at least 4:1 would satisfy both near term and long term heat demands.

The seasonality of wood waste availability must be considered. Appendix B shows higher production seasons (2nd and 3rd quarters) tend to generate more wood waste however this production also coincides with that time of the year when partial air drying can reduce the demands on a dry kiln. System design and sizing decisions cannot be based only on annual supply and demand averages because there might be periods with insufficient on-site wood waste to operate the kiln at full capacity, and other periods when excess wood waste must be disposed, stored or converted into an alternate energy output product. In general, energy output product selection, energy conversion equipment sizing, dry kiln sizing, and fuel storage sizing become complex interdependent considerations. Appendix C shows the lowest net energy availability at our specific site occurring in the 1st quarter. During the first two years it equals 1682 million Btu of which 952 million Btu can be obtained from wood waste needing no further drying. However the 1st quarter's dry wood waste is sufficient to accommodate that quarter's minimum heat requirement of 3600 million/4 = 900 million Btu.

The capital costs of constructing the general combustion/gasification/pyrolysis system depicted in Figure 6 are estimated for each subsystem. These estimates are compared in Appendix D, insofar as possible, with estimated or published capital costs of known commercial or potentially commercial units having the most likelihood of effectively performing each of the functions in our general system.

Conventional commercial wood waste combustion systems, gasification systems and pyrolysis systems can be very expensive, even running into the millions of dollars when elaborate fuel preparation and handling facilities are needed. A survey of 14 different commercial gasifiers (heat output only) sized from 1.5-72 million Btu per hour indicated capital costs ranged from $15,000 -

$30,000 per million Btu per hour capacity [46]. The estimated capital cost of our general system (Appendix D) per million Btu per hour capacity compares favorably with these commercial systems, with the added advantages of fuel versatility and the opportunity for multiple energy output products. The capital cost of the Enerco pyrolyzer [59,103] (designed to produce 43 million Btu per hour of gas, charcoal, and pyrolytic oil but no longer sold commercially) was approximately $700,000 (1980 price), or $16,300 per million Btu per hour.

It becomes critical, however, to distinguish between rated capacities and actual expected operating capacities when making system selection decisions. If constraints such as limited fuel availability preclude the system from ever sustaining operating levels near its rated capacity, then cost/effectiveness assessments based on rated capacities become suspect. Inspection of the fuel and energy availability profiles (Appendices B and C) indicate that much of the energy products that can be generated from on-site fuel will be needed in the form of heat for on-site lumber and fuel drying purposes. There is insufficient fuel on site to support either a pyrolytic oil or a charcoal production and marketing program for off-site use. Thus we are confronted with the probability that even if the general system demonstrated the desired versatility in multiple product outputs and overall cost/effectiveness based on rated output capacity, it likely would not be the most cost/effective choice based only on realizable output obtained from on-site fuel sources. The general system would be significantly underutilized due to fuel constraints, thereby making a short term investment payback difficult if only on-site fuel were used.

A cost/effective configuration needs to be identified that more readily accommodates the expected on-site fuel availability profile. For example, projected fuel availabilities appear not to be sufficient to sustain the long-term on-site heat requirements and a pyrolyzer subsystem. The preferred configuration, used for heat generation, would be the one that best uses those fuel types that have the lowest-value alternative uses like bark and sawdust. Coarse residue also might fall into this category, but the opportunity should be left open for later converting the coarse residue into higher valued pulp chips. Appendix C shows that even in the long run, coarse residue does not constitute a large percentage of the on-site fuel availability.

On a planning horizon of, say, 10 years there will be significant changes in both the heat requirement profile (more than doubling after two years) and the fuel availability profile (increasing by approximately 50% after two years, in

conjunction with a significant shift toward greater availabilities of bark and chip-type hog fuel and a greater likelihood that shavings will be diverted to other uses). These tranistory conditions suggest a lower cost sequential installation that initially can meet the energy demands in the short run and also be the most readily adaptable or expandable to accommodate unpredictable energy requirements and fuel types.

The most suitable form of energy to transfer from the selected system directly into a lumber drying facility would be gas obtained from a gasifier. Unlike flue gas from an incinerator, the gas from a gasifier can be essentially free of sparks, ash, etc., and can be ignited at convenient locations in the drying facility. The inclined pinhole grate gasifier recommended for the general system might be used in this fashion. Its design has the advantage of being readily expandable for higher outputs (probably over 10 million Btu per hour) by extending the width of the refractory slide comprising the pinhole grate. Its design would be well suited for a homogeneous fuel that is dry and uniformly sized. Homogeneity is important in order to prevent channeling or hot spots from occurring because the fuel bed must continue to replenish and spread uniformly down the inclined grate primarily through the tumbling or sliding of the individual fuel particles. In order to keep the particle interaction throughout the entire depth of the fuel bed tenuous so this tumbling and sliding distribution down the bed can proceed uniformly, the slope of the bed should parallel the particular fuel's angle of repose. This angle can vary with different fuel types. Minor differences in fuel types might be overcome by introducing agitation at the bottom of the fuel bed, such as some type of moving agitator or grate system at the bottom of the inclined pinhole grate. One suggestion for the agitator would be a shallow bed of mullite pebbles [17,p.30] or marble-sized ceramic beads on top of a moveable perforated metal plate or grate. The beads would be subject to the same high temperatures as the refactory inclined pinhole grate and would tend to protect the metal grate. Ash would gravitate down through the beads and metal grate onto an ash auger for removal.

The longer term on-site fuel profile as seen in Appendix B will be changing, away from shavings and toward sawdust, bark and a chip-type hog fuel. The fuel characteristics of the latter two will approximate those of small chips (slightly smaller than suitable for pulp chips). This reduction in shavings use and increase in sawdust use may cause some problem for the inclined pinhole grate, as it may not be as adaptable to this change as some other design enabling better control

of the fuel bed environment. These future on-site fuels might be gasified if the fuel could fall straight down into the gasification chamber, could be kept from bridging, could be agitated uniformly and more closely to where gasification takes place, and if the transfer rate of air through the fuel bed could be regulated according to the density difference (i.e., resistance to air flow) of each fuel type.

One type of gasifier that might accommodate the future on-site fuel types is a modified stratified downdraft gasifier [86]. Traditionally, conventional downdraft gasifiers have not been able to operate successfully on fuel particles much smaller than chips. Fuel particles for commercial downdraft gasifiers are generally recommended to be dry, uniformly sized, and as large as or larger than chip size, or densified into larger pellets or cubes if smaller [104].

The characteristics of the on-site bark and chip-type hog fuel are compatible for use in this type of gasifier. However, the problem encountered with using small fuel particles such as sawdust in this type of gasifer is the excessive pressure drop incurred through such a fuel bed in order to maintain a given level of air (and gas) throughput. For example in a one foot deep sawdust fuel bed, the resistance to air flow at 110 ft/minute velocity is approximately ten times that encountered in typical chip or bark fuel beds [104,p.149]. For this reason, the successful use of sawdust in conventional downdraft gasifiers has been evasive, although some evidence exists that with a sufficiently high induced draft to overcome this resistance, gasification can be sustained at acceptable throughput rates [75]. A change in fuel type input, say from chips to sawdust, requires some provision for adjusting the fuel bed parameters (depth, resistance, etc.) accordingly. This might be done by means of (1) compensating for the increased pressure drop by increasing the induced draft, (2) changing the air inflow configuration to reduce ostensible bed depth (e.g., lowering air inlets or nozzles further down into the bed), and/or (3) controlling the fuel inflow rate to reduce actual bed depth.

Some combination of the above adjustments might accommodate a change in fuel type even during operation as long as fuel characteristics remain acceptably uniform horizontally within the fuel bed as the change takes place. Vertical non-uniformity in the fuel bed would not be acceptable as it would cause an uneven pressure drop in different vertical sections of the fuel bed, resulting in channeling, cold spots, and ungasified fine material being prematurely drawn through the grate and entrained in the exiting gas. With the aid of fuel levelers,

maintenance of horizontal fuel bed uniformity is compatible with our original intention to continue keeping different fuel types separate and diverting them into the process as needed.

The schematic of a simple stratified downdraft gasifier appears in Figure 7 [see reference 86 for additional details]. Modifications are needed for this type of gasifier to accommodate the types of fuel we expect to be using in the long run (from sawdust size up to chip-sized hog fuel and bark). The design presented in Figure 8 depicts our proposed modifications for making this type of gasifier function on these fuels. The central rotating structure prevents fuel bridging and accomplishes fuel leveling, fuel bed agitation, metal grate and mullite pebble rotation for ash removal, and delivery of air into the bed at an appropriate (and variable) height above the grate. Unlike the "Buck" Rogers downdraft gasifier [19] where unheated air comes in from above and enters at a fixed height above the grate, the proposed design in Figure 8 brings the air (usually pre-heated) up a tube from below and directs it to the particular height above the grate that is most suitable for the fuel type in the fuel bed. This incoming air is diverted into those nozzles at the proper height through a slotted cylindrical sleeve that, when rotated into different quadrants relative to the central tube, directs the air into the proper set of nozzles.

To ensure proper gasification and avoid cool surfaces in the reduction zone of the fuel bed, it is necessary to either keep temperatures of the air coming up through the central tube high (by preheating) or to insulate between the tube and the sleeve to avoid cooling the reduction zone. One might investigate the possible benefits of recycling hot gas with, or instead of, air up through the tube and into the fuel bed. A decrease of tar content in the final gas output can be expected [97]. However, unless the gas is being used in an internal combustion engine, turbine, etc. this additional decrease of tar is usually unnecessary because tar content in gas produced from this type of downdraft gasifier is already quite low (well under 1%) [86]. If the gas is burned before recycling, an increase of the Btu heat content of the gas can be expected because limited oxygen in burned gas encourages less gasification and more pyrolysis.

From Appendix C we see that the on-site fuel types best suited for use in the proposed downdraft gasifier (namely, the chip-type hog fuel and the chip-sized bark) will not occur in significant quantities for the next two years. In the meantime there is sufficient sawdust, if dried, to provide the minimum near-term heat requirements. In order to avoid the need for fuel drying in the

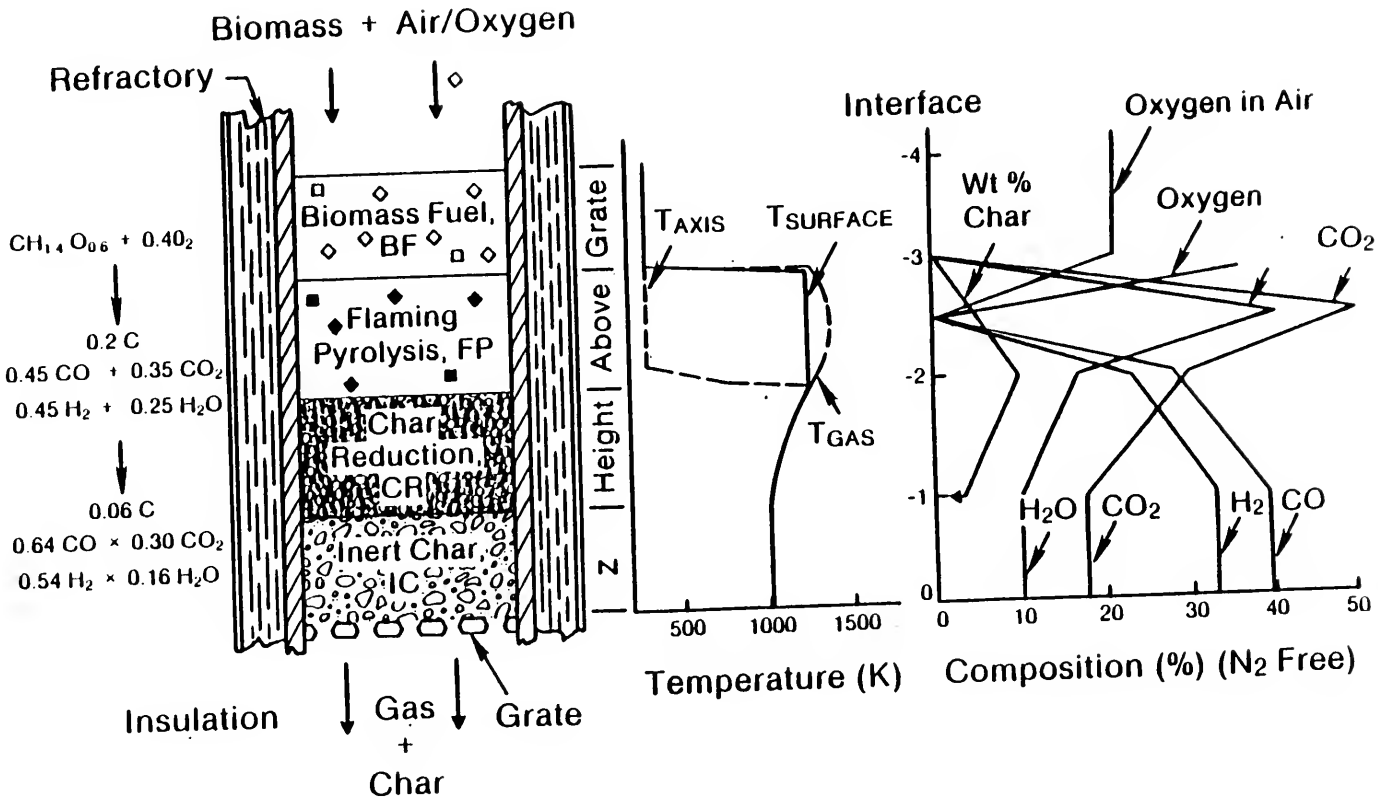


Figure 7. Schematic of Stratified Downdraft Gasifier Showing (a) Chemical Reactions, (b) Temperature Profiles, and (c) Composition. From Reed, reference 86.

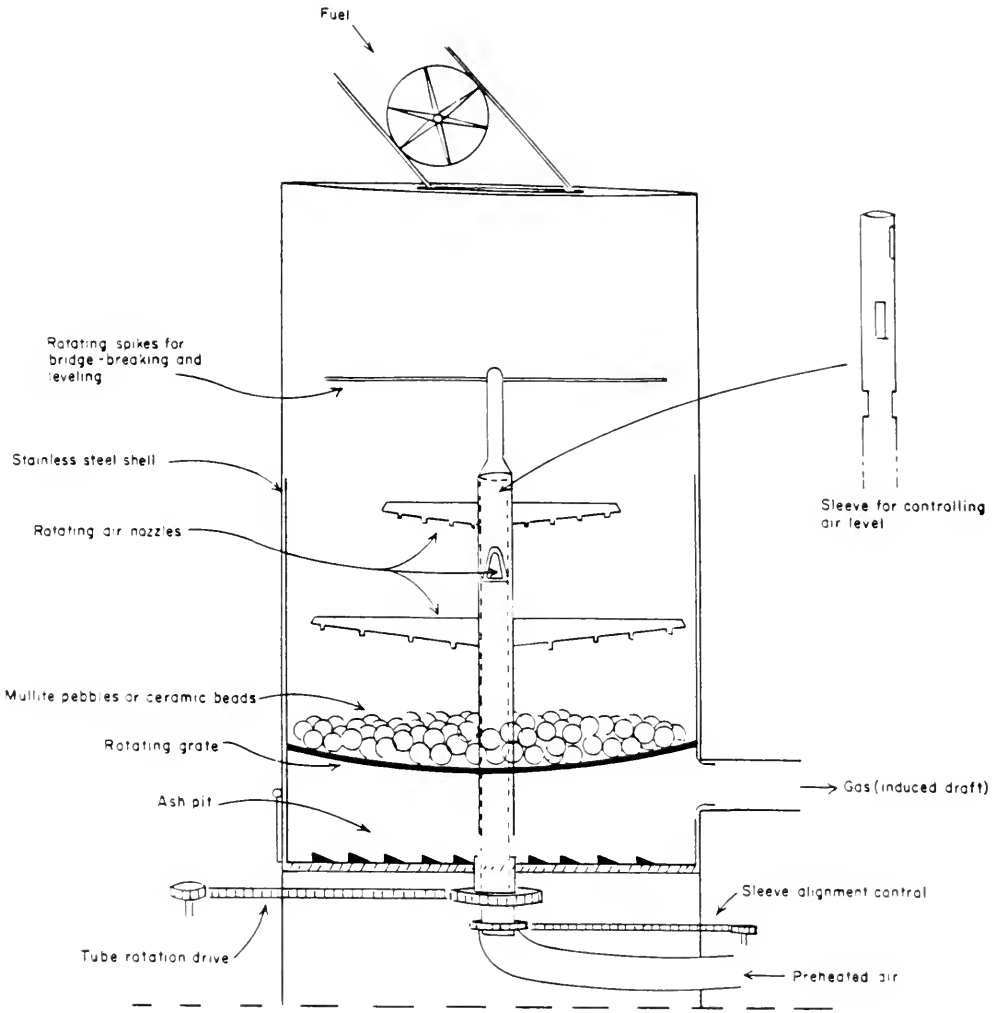


Figure 8. Modified Downdraft Gasifier

near term, dry shavings would be used to provide much of the heat. Unfortunately, unprocessed (i.e., non-densified) shavings do not perform well in conventional downdraft gasifiers because of severe channeling problems. It is possible, however, that if the shavings were crushed or fractured by running through a simple axial fan and then mixed with sawdust, the fuel bed densities might be adequate to sustain stable gasification conditions. The mullite pebble bed should help keep the lighter particles in such a mix from becoming entrained in the exiting gas.

PERFORMANCE MEASURES, MASS AND ENERGY BALANCES

Estimated performance measures for the proposed downdraft gasifier include expected energy outputs, gas composition and heating values, mass and energy balances and energy conversion efficiencies. Empirical and analytic data [54,97,102,104] obtained from downdraft gasifiers designed to operate under similar conditions and on similar fuel types to those intended for our proposed system show general concurrence in expected performance measures. Summarily, we can expect that for typical wood waste with low moisture content (under 20%) and low ash content (under 5%):

1) Expected dry gas yield will be 35-40 standard cubic feet (scf) per pound of dry wood with an expected gas heating content of 140-170 Btu per scf,
2) Expected gas composition (dry basis) will be 10%-15% CO_2, 19%-23% CO, 12%-18% H_2, 45%-53% N_2, and 2%-5% hydrocarbons,
3) Expected mass conversion will be 85%-90% gas, 2%-8% char, 2%-5% ash, and less than 1% oil/tar,
4) Expected energy conversion will be 65%-75% gas energy (cold gas basis), 3%-10% char energy, 0%-1% oil/tar energy, and 5%-10% sensible heat (recoverable).

SIZING THE GASIFIER AND DRYER

Assume a fuel energy content of 8500 Btu per pound of dry wood waste and assume an 85% efficiency in converting this fuel to heat (say, 75% from burning the gas and 10% in recovering sensible heat from the gasifier). Previous analysis suggests that a 3 million Btu per hour gasifier design is needed. The hourly maximum fuel consumption for this design would be 3 million/(.85x8500) = 415 lb/hour. A typical gasification rate for well designed downdraft gasifiers operating on dry wood is approximately 90 pounds of fuel per hour per square foot of cross-sectional area of grate [104,p.159]. Therefore the circular grate area of the gasifier should be 415/90 = 4.6 sq. ft., or approximately 29 inches in diameter. Height of the grate is approximately equal to the diameter.

Because some fuel need not be dried and some dry fuel storage will be available, a fuel dryer with 400-500 lb/hour drying capacity would be adequate. If shavings can be inexpensively fractured and mixed with sawdust to obtain a sufficiently dense and uniform fuel bed, very little drying may be needed.

COST PROJECTIONS AND SAVINGS

The modified downdraft gasifier proposed in the preceding section accommodates the on-site fuel availability profile and is likely to be the most cost/effective in providing the required energy outputs for the on-site lumber drying application. Estimated capital, operating and fuel costs for this system are presented in Appendix E.

The capital costs in Appendix E are assumed to be annualized over the estimated 10 year useful equipment life and reflect a 10 year self-amortizing monthly payment loan at 18% interest (or equivalently reflect, if internally financed, a minimum required internal rate of return on invested capital of 18%). Total costs including annualized capital costs, operating costs, and fuel costs result in a gas output cost of $1.61 per million Btu from the proposed system when operated at an assumed 5000 hours per year.

If lumber drying were to be done with a fossil fuel such as No. 6 fuel oil (natural gas is not available on site), in a direct-fired oil burning furnace, estimated costs would be as shown in Appendix E. Total costs of that system result in an output cost of $9.03 per million Btu when operated at the assumed 5000 hours per year. Comparing the gasifier system with the oil fired system, it can be seen in Appendix F that the simple payback period of the gasifier system compared to the oil fired system is exceedingly short, less than five months.

SENSITIVITY ANALYSIS

The proposed system has a much higher initial fixed capital cost than the oil fired system, and therefore the cost per million Btu from the proposed system would be quite sensitive to low system utilization because this high fixed cost must be absorbed in fewer output units at lower operating levels. The oil fired system on the other hand has low initial fixed capital costs and high variable (i.e. fuel) costs. Sensitivity of the two systems to low operating levels and other pessimistic cost assumptions are investigated in Appendix F. If operating levels are half that expected (2500 hours per year), the cost of labor to run the proposed gasifier system three times that expected, gasifier maintenance 150% higher than expected, electrical power 50% higher than expected, and wood-waste fuel costs 100% higher than expected, then the expected cost for the gasifier output increases from $1.61 to $5.16 per million Btu, still a substantial savings over the oil fired system, with simple payback only slightly more than one year.

IMPLEMENTATION AND MARKETABILITY

Implementation and marketability of the proposed system require consideration of necessary permits, financing, and its applicability for use at other sites.

PERMITS

Section 16.8.1102 of the Montana Air Quality Rules states that a construction and operating permit is not required for any potential air contaminant source that burns gaseous or liquid fuels less than 10 million Btu/hour, or burns solid fuels less than 5 million Btu/hour. Therefore the proposed downdraft gasifier qualifies for the permit exclusion. The proposed general combustion/gasification/pyrolyzer also would likely qualify for this exclusion. The use of catalytic combustors and an afterburner would enable the general system to easily meet both state and federal pollution control standards.

FINANCING

The potential profit enhancement of having year-round lumber drying capability on site, and the rapid payback obtained by utilizing wood waste for this drying compared to such alternatives as using fossil fuel should enable conventional financing sources to see the benefit of loaning capital on such a system. There are also, however, sources of financing obtainable from limited partnership structures in which tax advantages such as investment tax credits, energy tax credits, etc. can be transferred to the lending parties. These sources should be considered as a possible means of obtaining a favorable financing package for such a system.

APPLICABILITY TO OTHER SITES

The final selection of the system design was made in accordance with constraints (mostly related to fuel types) specific to the site being examined. The proposed modified downdraft gasifier could be used at sites with similar fuel availability profiles, and conventional gasifiers have wide applicability to numerous sites in the forest products industry. The proposed general combustion/gasification/pyrolysis system merits further development and evaluation where fuel types and availabilities are sufficient to meet total

requirements for the desired on-site energy output products and also in sufficient surplus to enable the establishment of viable markets for storable and transportable energy output products such as charcoal and pyrolytic oil.

CONCLUSIONS AND RECOMMENDATIONS

In view of the particular on-site energy requirements (primarily heat) and the unique and changing on-site wood-waste fuel types and availabilities, a conservative system design has been selected that can effectively accommodate the changes expected to occur in these on-site requirements, fuel types and fuel availabilities. As these changes materialize, the system can be modified or expanded accordingly. The basic recommended system design is a modified downdraft gasifier that initially will generate a low Btu gas that will be burned for drying lumber and wood waste fuel. Later, the gas also could be used in the afterburner of a combustion or incineration chamber in conjunction with catalytic combustors to ensure complete combustion of particulates from that subsystem. Further, the gas might be used later to provide heat for a pyrolyzer subsystem. Existing and anticipated site characteristics and cost/effectiveness considerations favor this conservative initial configuration over a more elaborate multiproduct system.

APPENDIX A

Catalytic Combustor Design Considerations

Detailed engineering information useful for the design, implementation and operation of catalytic combustor units is available in Reference 4 and Reference 22. The general integrated energy system would use multiple standarized replaceable catalytic combustor units as shown in Figure 9.

Catalytic Combustor Shape

The most efficient cross sectional shape for catalytic combustor units is round. It has the least flow resistance and the most homogeneous distribution of gases.

Catalytic Combustor Size

A commercially available standardized combustor unit is desired. The size most readily obtainable is the 5½" diameter, 3" long unit.

Cell Size

Cell densities of 16 - 20 cells per square inch are recommended in order to accommodate the low induced-draft pressures expected, to minimize pressure drop, and to avoid ash and creosote clogging.

Mounting

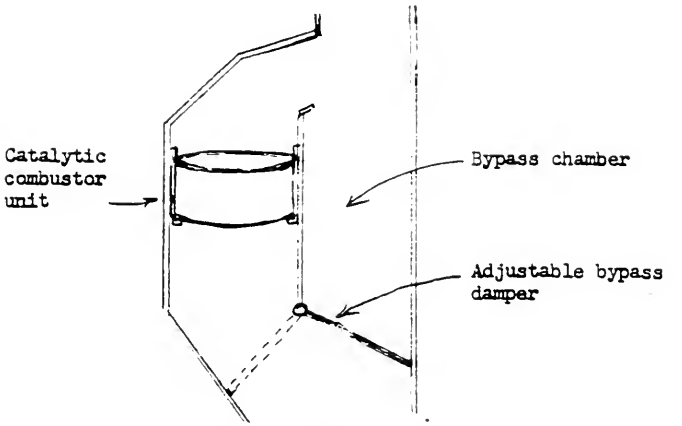
Catalytic combustor units must be mounted in a position so the flue gases flow upward through the cell structure. The high temperature output from the catalytic combustor unit should impinge on the output from the bypass. This impingement will induce complete combustion of the portion of the flue gas coming through the bypass, and thereby make total flue-gas flow through the catalytic combustor units unnecessary.

Bypass Design

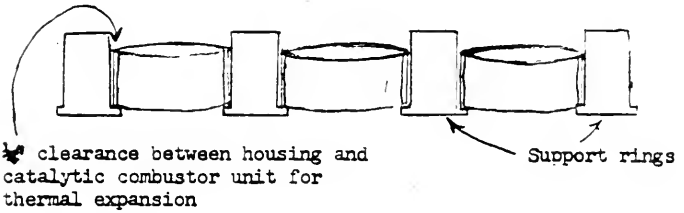
The bypass should be sized large enough to provide for unrestricted passage of total flue-gas flows when burning conditions make it necessary to pass any portion of the flue gas through the catalytic combustor units. An adjustable damper should be able to divert a varying proportion of the flue gas through the catalytic combustor units as needed.

Number of Catalytic Combustor Units

A general integrated energy system containing a combustion chamber rated at 2 - 3 million Btu per hour should be able to maintain acceptable combustion performance with 6-10 standard sized catalytic combustor units in conjunction with a gasifier afterburner.



Side view of bank of catalytic combustor units



Face view of bank of catalytic combustor units

Figure 9. Catalytic Combustor Configuration

APPENDIX B

Bone Dry Tons of Wood Waste

First Two Years:	1st. Quarter	2nd. Quarter	3rd Quarter	4th Quarter	Totals
Green Sawdust	35 tons	90	125	35	285
Dry Sawdust	10	15	20	10	55
Green Shavings	9	9	9	9	36
Dry Shavings	36	36	72	36	180
Green Coarse Residue	5	5	5	5	20
Dry Coarse Residue	10	22	44	20	98
Green Chip-Type Hog Fuel (non-pulp)	0	0	0	0	0
Green Bark	0	0	0	0	0
Totals	105	177	275	115	672

After Two Years:					
Green Sawdust	48	94	140	48	330
Dry Sawdust	11	16	22	11	60
Green Shavings	10	10	10	10	40
Dry Shavings	40	40	80	40	200
Green Coarse Residue	10	10	10	10	40
Dry Coarse Residue	22	44	90	44	200
Green Chip-Type Hog Fuel (non-pulp)	30	30	30	30	120
Green Bark	25	25	25	25	100
Totals	196	269	407	218	1090

APPENDIX C

Net Btu Content of Available Fuel*
(millions of Btu)

First Two Years:	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	Totals
Green Sawdust	521	1341	1863	521	4246
Dry Sawdust	170	255	340	170	935
Green Shavings	134	134	134	134	536
Dry Shavings	612	612	1224	612	3060
Green Coarse Residue	75	75	75	75	300
Dry Coarse Residue	170	374	748	374	1666
Totals	1682	2791	4384	1886	10,743
After Two Years:					
Green Sawdust	715	1400	2086	715	4916
Dry Sawdust	187	272	374	187	1020
Green Shavings	149	149	149	149	596
Dry Shavings	680	680	1360	680	3400
Green Coarse Residue	149	149	149	149	596
Dry Coarse Residue	374	748	1496	748	3366
Green Chip-Type Hog Fuel (non-pulp)	447	447	447	447	1788
Green Bark	373	373	373	373	1492
Totals	3074	4218	6434	3448	17,174

*Net Btu content for the dry fuel is 17 million Btu per bone dry ton [Ref. 49]. Net Btu content for the green fuel is obtained by adjusting dry fuel Btu content downward by that portion needed to reduce the green fuel moisture content to that of the dry fuel moisture content. For this site, approximately 0.7 pounds of water per bone dry pound of fuel needs to be removed to convert the green fuel to the same dryness as the dry fuel. Conventional wood-waste drying methods require approximately 1500 Btu of heat per pound of water removed [Ref. 76]. Therefore, the net available Btu content for the green fuel is estimated at 17 million - (0.7x1500x2000) = 14.9 million Btu per bone dry ton.

APPENDIX D

General System Costs*

Combustion Subsystem	$15,000
Catalytic Combustor Subsystem	5,000
Inclined Grate Gasifier Subsystem	15,000
Pyrolyzer Subsystem (including dryer tube system)	10,000
Interface Controls & Instrumentation	10,000
Installation, Freight, etc.	5,000
Subtotal	$60,000
Fuel Handling Equipment	3,000
Fuel Dryer (shuffleboard type, 800-1000 pounds per hour, dry basis)	5,000
Fuel Storage (two 8'x 8'x40' chip vans)	7,000
Total	$75,000

Cost per million Btu per hour = $75,000/5 = $15,000 per million Btu per hour.

*Estimated capital costs include hardware, component and instrumentation costs, labor costs for fabrication and installation. Not included are elaborate fuel preparation, handling and storage facilities, engineering design and testing costs, or operator training costs.

APPENDIX E

Costs of the Modified Downdraft Gasifier, with Comparisons

Capital Costs[1]	Modified Downdraft Gasifier System	Fossil Fuel System (fuel oil)
Gasifier (3 million Btu per hour capacity)	$10,000	$2,000
Fuel Dryer (shuffleboard type, 400-600 pounds per hour, dry basis)	3,000	-
Fuel Handling Equipment	3,000	-
Fuel Storage (two - 8'x8'x40' chip vans)	7,000	500
Instrumentation and Controls	5,000	1,000
Installation, Miscellaneous	4,000	500
Total Capital Costs	$32,000	$4,000
Annualized Capital Costs[2] (Gasifier = $575/month; Fuel Oil System = $72/month)	$6,900/yr	$860/yr
Operating Costs (5000 hrs/yr, 10,000 million Btu/yr):		
Labor 2 hrs/day x 208 days/yr x $10/hr	4,160	
1 hr/week x 52/yr for fuel oil system		520
Maintenance (2% of capital costs[3])	640	80
Electrical power (10 hp, 95% motor efficiency, 50% load factor, 5¢/kwh)	900	-
Fuel Costs		
$5/ton x 700 tons/yr, dry basis[4]	3,500	
$8/million Btu x 10,000 million Btu/yr ÷ 90% burner efficiency		88,880
Total Annualized Capital, Operating, and Fuel Costs	$16,100/yr	$90,340/yr
Cost per million Btu	$1.61	$9.03

Net annual operating and fuel savings = $89,480 - $ 9,200 = $80,280

Simple payback period[5] = Total additional capital cost — annual savings

= ($32,000 - $4,000)/80,280 = .35 years
= less than 5 months

1. See footnote, APPENDIX D.

2. Capital Costs are annualized over their estimated 10 year useful life, equivalent to a 10 year self-amortizing monthly payment loan @ 18% interest.

3. See Reference 46, p. 11.

4. Current wood waste cost = $0; however the wood waste to be used on-site for fuel is expected to have an average alternative value (i.e., opportunity cost) of $5 per bone dry ton. A breakeven calculation shows that wood fuel costs would have to exceed $100 per bone dry ton before would fuel would cease to be competitive with fuel oil under the stated assumptions.

5. See Reference 46, p. 14.

APPENDIX F

Sensitivity Analysis

	Modified Downdraft Gasifier System	Fossil Fuel System (fuel oil)
Annualized Capital Costs (See APPENDIX E)	$6,900/yr	$ 860/yr
Operating Costs (2500 hrs/yr, 5000 million Btu/yr)		
Labor 6 hrs/day x 208 days/yr x $10/hr =	12,480	
1 hr/week x 52 week/yr x $10/hr =		520
Maintenance (5% of capital costs)	1,600	200
Electrical Power (7.5¢/kwh)	1,300	-
Fuel Costs		
$10/ton x 350 tons/yr, dry basis =	3,500	
$8/million Btu x 5000 million Btu/yr ÷ 90% burner efficiency =		44,440
Total Annualized Capital, Operating, and Fuel Costs =	$25,780/yr	$46,020/yr
Cost per million Btu =	$5.16	$9.20

Net annual operating and fuel savings = $45,160 - $18,880 = $26,280

Simple payback period = Total additional capital cost ÷ annual savings

= ($32,000 - 4,000)/26,280 = 1.07 years
= approx. 13 months

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55. Keown, William H. "A Parametric Analysis of Wood Pyrolysis Gas as an Alternate Fuel for a Small Gas Turbine Engine," paper presented at the Seventh International FPRS Industrial Wood Energy Forum, Nashville, Tennessee, September 19-21, 1983.

The proposed design of a small-scale, close-coupled, medium-BTU pyrolysis system is presented. It is a closed, indirectly heated reactor system configured as a free-turbine engine operating in a reheat mode.

56. Klass, Donald L., editor. Biomass as a Nonfossil Fuel Source. Washington, D.C.: American Chemical Society, 1981. (Based on ASC Symposium, Honolulu, Hawaii, April 2, 1979)

The text is based on papers presented at the ACS Symposium held in Honolulu, Hawaii, April 2, 1979. Technologies for converting biomass to fuel oils, gases and other forms of non-petroleum sources of energy are described.

57. Klass, Donald L. "Energy from Biomass and Wastes: 1982 Update," paper presented at the Energy From Biomass and Wastes VII Symposium, Lake Buena Vista, Florida, January 24-28, 1983.

58. Kleensmoke, Inc. Product literature. 22 Franklin Ave., Willits, California 95490

59. Klein, E. Lawrence. "Tennessee Valley Authority's Pyrolysis Project," paper prepared by Division of Land and Forest Resources, TVA, Norris, Tennessee, 1980.

60. Knight, J.A., D.R. Hurst, and L.W. Elston. "Catalytic Conversion of Biomass to Useful Fuels," report prepared at Georgia Institute of Technology Engineering Experiment Station, Atlanta, Georgia, Project A-2494-001, December 1980.

In Georgia Tech's tube furnace, various catalysts are evaluated for their relative usefulness in generating high yields of noncondensible gas and enhancing the recovery of oil condensate. Results suggest that transition metal catalysts such as iron compounds in conjunction with alkali metal carbonate catalysts (e.g., potassium carbonate and wood ash) are attractive candidates.

61. Knight, J.A., et al. "Entrained Flow Pyrolysis of Biomass," Proceedigs of the 15th Biomass Thermochemical Conversion Contractor's Meeting, Atlanta, Georgia, March 16-17, 1983, pp. 409-420.

62. Krochta, J.M., et al. "Thermochemical Conversion of Biomass to Liquid Fuels," paper No. 82-3098 presented at American Society of Agricultural Engineers meeting, U. of Wisconsin-Madison, June 27-30, 1982.

Research results show that thermochemical conversion in water produces more water-soluable and acetone-soluable products and less residue than dry pyrolysis. Sodium hydroxide and sodium carbonate are equally effective catalysts.

63. Krochta, J.M. and J.S. Hudson. "Alkaline Digestion of Biomass to Chemicals and Fuels," Paper No. 82-3608 presented at American Society of Agricultural Engineers meeting, Chicago, Illinois, December 14-17, 1982.

Addition of alkali catalysts can be adjusted to generate more or less acetone soluables and more or less water soluables (such as alcohols, ketones and carboxyhe acids).

64. Kuester, James L., Gary W. Heath and Ta-Ching Wang. "Diesel Fuels from Biomass Derived Synthesis Gas," paper presented at the Catalytic Conversion of Pyrolysis Gases Symposium, AIChE Annual Meeting, Los Angeles, November 14-19, 1982.

Describes research at Arizona State University for producting diesel fuel from biomass by gasification followed by liquefaction. Three fluidized bed reactors are used. Potentially over 50 gallons of diesel fuel may be obtained per ton of dry biomass.

65. Lamb Cargate Industries Ltd. Product Literature. P.O. Box 440, 1135 Queens Avenue, New Westminister, B.C., Canada V3L 4Y7.

66. Layne, Richard. "This Gas Turbine Burns Sawdust," Popular Science, Vol. 225, No. 5, Nov. 1984, p. 65.

67. Levelton, B.H. An Evaluation of Wood Waste Energy Conversion Systems, ENFOR Project C-111, Vancouver, B.C.: B.H. Levelton & Associates, Ltd, December 1980.

Wood residue energy conversion equipment is categorized and evaluated. Combustors, gasifiers, pyrolysis systems, densification equipment and process controls are discussed.

68. Lewis, F.M. and C.M. Ablow. "Pyrogas from Biomass," paper presented in Proceedings: Capturing the Sun Through Bioconversion, Washington, D.C., March 10-12, 1976, pp. 341-356.

Described the use of an indirectly heated rotary kiln enclosed in a refractory-lined firebox to generate producer gas. A portion of this gas is burned in the annular space between the outside of the cylindrical retort and the inside of the firebox. The output of the system is partially activated charcoal and producer gas.

69. Lewis, F.M. and C.M. Ablow. "Thermodynamics of Pyrolysis and Activation in the Production of Waste- or Biomass-Derived Activated Carbon," paper appearing in Thermal Conversion of Solid Wastes and Biomass edited by Jerry L. Jones and Shirley B. Radding, American Chemical Society, ACS Symposium Series 130, Washington, D.C., 1980, pp. 301-314.

70. Limaye, Dilip and Shahzad Qasim. Montana Biomass Cogeneration Manual, prepared for Biomass Cogeneration Workshop sponsored by Montana Department of Natural Resources & Conservation and U.S. Department of Energy. Bala Cynwyd, Pennsylvania: Synergic Resources Corporation, May 1983.

This manual describes cogeneration technologies and biomass fueled cogeneration systems and manufacturers/suppliers.

71. Lindsley, E.F. "Sodium + Sunshine = Electricity," Popular Science, Vol. 223, No. 6, December 1983, pp. 22-24.

Ford Motor Company's Scientific Research Center has developed a sodium heat engine that converts heat directly into electricity. Heat of 1300[-1800[F from any source is sufficient, and the engine has no moving parts.

72. Jasper, Martin T. and Peter Koch. "Suspension Burning of Green Bark to Direct-Fire High-Temperature Kilns for Southern Pine Lumber," Wood Residue as an Energy Source, Proceedings No. P-75-13 held in Denver, September 3-5, 1975, published by Forest Products Research Society, Madison, Wisconsin, 1975, pp. 70-72.

A low-cost suspension burner is described that could burn green bark. Fuel preparation would need to ensure that the fuel particles be sized less than 3/16 inch. The combustion chamber of the burner is an annular space between two concentric vertical cylinders, with the inner one housing a vertical down-feeding auger.

73. Massoudi, M.S. "Burning Behavior of Wood Slabs in Reactive Environment." Wood Science, Vol. 10, No. 4, April 1978, pp. 176-180.

Experimental results indicated that the burning rate is far more sensitive to wood thickness than it is to combustion air-flow, combustion zone temperature, or moisture content.

74. Mc Gowan, Thomas F., Anthony D. Jape and James L. Walsh. "Utilization of Waste Streams in Biomass Gasifiers," Proceedings of the 15th Biomass Thermochemical Conversion Contractor's Meeting, Atlanta, Georgia, March 16-17, 1983, pp. 223-235.

75. Missouri Gasification Systems, Inc. Product literature. R.D. 3 - Box 98, California, Missouri 65018.

76. Moore, William E. "Mill Residues; What Are They Really Worth?" paper appearing in Wood Residue as an Energy Source. Madison, Wisconsin: Forest Products Research Society, Proceedings No. P75-13, 1975, pp. 21-26.

77. Mudge, L.K., et al. Investigations on Catalyzed Steam Gasification of Biomass, PNL-3695, Pacific Northwest Laboratory, Richland, Washington, January 1981.

Compares catalytic steam gasification of biomass to conventional gasification. Reports results of laboratory studies conducted to develop operating conditions suitable for generating methane-rich gas. A detailed economic analysis is presented.

78. Mudge, L.K., et al. Catalytic Gasification Studies in a Pressurized Fluid Bed Unit, PNL-4594, Pacific Northwest Laboratory, Richland, Washington, July 1983.

Sodium carbonate and potassium carbonate are effective catalysts for converting biomass to methane-rich gas in a pressurized gasifier. The economics compare favorably to previous research results obtained under non-pressure conditions.

79. National Synfuels, Inc. Product literature. P.O. Box 40239, Jacksonville, Florida 32203.

80. Ontario Research Foundation. Rapid Gasification of Wood Waste, ENFOR Project C-18. Mississauga, Ontario: Ontario Research Foundation, July 1979.

Two rapid wood gasification systems are evaluated. One involves a jet burner, the other an external counter-current gasifier.

81. Powell, Evan. "How to Get Every Last BTU from Your New Catalytic Wood Burner," Popular Science, Vol. 221, No. 4, October 1982, pp. 221-223.

Catalytic combustors are described. They increase combustion efficiency and reduce fuel requirements by about one-third. Long burn times are obtainable when properly operated.

82. Rambush, N.E. Modern Gas Producers. London: Benn Brothers, Limited, 1923.

Detailed descriptions are provided of producer-gas generating equipment built in the early 1900's. Numerous graphs and engineering data are presented.

83. Reed, Thomas G., ed. Generator Gas: The Swedish Experience from 1939-1945, SERI/SP-33-140, Solar Energy Research Institute, Golden, Colorado, January 1979.

Technical and commercial development of gas generators in Sweden during and prior to World War II is described. Details on reactor designs, operating characteristics, fuel preparation problems, etc. are provided. Sweden converted 40% of its entire motor vehicle fleet to the burning of wood during the war.

84. Reed, T.B., et al. Survey of Biomass Gasification, Volumes I-III, SERI/TR-33-239. Golden, Colorado: Solar Energy Research Institute, 1980.

This has been published in hardcover. See: Reed, T.B., ed. Biomass Gasification: Principles and Technology, Energy Technology Review No. 67, Park Ridge, N.J.: Noyes Data Corp., 1981.

85. Reed, T.B. ed. Biomass Gasification: Principles and Technology, Energy Technology Review No. 67, Park Ridge, N.J.: Noyes Data Corp., 1981.

This text represents a survey of the technical background of biomass gasification, the status of present research being conducted, and recommendations for future research and development. Specific kinetics and thermodynamics of gasification reactions are discussed.

86. Reed, T.B. and B. Levie. "A Simplied Model of the Stratified Downdraft Gasifier," paper presented at the Seventh International FPRS Industrial Wood Energy Forum, Nashville, Tennessee, September 19-21, 1983.

A predictive model useful for designing downdraft gasifiers is presented. Interactive variables are pyrolysis time, heat transfer rate, char gasification time, zone length, etc.

87. Rettew Automation, Inc. Product literature. Box 65, N. Sheridan Rd., Newmanstown, Pennsylvania 17073

88. Robinson, J.S. Fuels From Biomass. Park Ridge, New Jersey: Noyes Data Corporation, 1980.

Presents an excellent discussion of gasification and pyrolysis processes. Commercial and research activities in this field are reviewed. For example the Garrett multiple hearth process is described.

89. Ross, Robert A. and Peter Fong. "Catalytic Conversion of Wood Barks to Fuel Gases," Industrial & Engineering Chemistry Product Research and Development, Vol. 20, 1981, pp. 197-203.

Indicates how gasification temperature can be lowered and heat content of producer gas raised by using K_2CO_3, potassium carbonate, as a catalyst.

90. Rowell, R.M., G.J. Hajny, and R.A. Young. "Energy and Chemicals from Wood," Chapter 19 in Introduction to Forest Science, edited by Raymond A. Young, U. of Wisconsin. New York: John Wiley & Sons Inc. 1982, pp. 451-469.

The use of biomass as a course of energy, liquid fuels and chemicals is discussed, and several alternatives for doing this are presented.

91. Sarkanen, Kyosti V. and David A. Tillman, eds. Progress in Biomass Conversion, Volume I. New York: Academic Press, 1979.

Energy uses for biomass are presented in a compilation of contributed papers. Conversion technologies and problems are discussed.

92. Savsar, Mehmet and Paul C. Kersavage. "Mathematical Model for Determining the Quantity of Materials Produced in Sawmilling," Forest Products Journal, Vol. 32, No. 11/12, Nov/Dec 1982, pp. 35-38.

A computer simulation program is presented that uses a mathematical model to determine relative volumes of flitches, sawdust, slabs, edgings, trims, etc. It assumes logs are truncated cones (equations are given) and are sawn parallel to log axis.

93. Schiefelbein, Gary F., Don Stevens and Mark Gerber. "Overview of DOE's Thermochemical Conversion Program," paper presented at the Seventh International FPRS Industrial Wood Energy Forum 1983, Nashville, Tennessee, September 19-21, 1983.

94. Schneider, Jason. "Catalytics Come of Age!" The National Energy Journal, Vol. 5, No. 8, June 1983, pp. 23-30.

This article is a good review of recent technological improvements that have been made in the construction and practicality of catalytic combustion units. Manufacturers of catalytic combustors are listed, as are companies that are incorporating the combustors in their final products.

95. Shelton, Jay W. and Jane W. Mc Grath. "Cleaner and Hotter Wood Heat," Rodale's New Shelter, Vol. 4, No. 7, September 1983, pp. 50+.

96. Soltes, Ed. J. and Shih-Chien K. Lin. "Vehicular Fuels and Oxychemicals from Biomass Thermochemical Tars," paper presented the Biotechnology and Bioengineering Symposium No. 13, 1983.

Biomass thermochemical tars obtained from gasification and pyrolysis under catalytic conditions appear to provide a good source of diesel- and gasoline-type fuels, and oxychemicals. The types of biomass feedstock may differ considerable, but still yield very similar products.

97. Susanto, H., A. Beenackers and W. Swaaij. "Moving Bed Gasifier with Internal Recycle of Pyrolysis Gas," paper presented at International Producer Gas Conference, Sri Lanka, November 1982.

98. Synergic Resources Corporation. Evaluation of Dual Energy-Use Systems, EPRI EM-2695, Electric Power Research Institute, October 1982.

Potential applications of industrial cogeneration and district hearing are evaluated. Systems analysis, methodology and computerized analytic tools for making these evaluations are developed. These are used to propose conceptual designs of more cost/effective cogeneration systems.

99. Thornton, Mark M. and Philip C. Malte. "Analysis of Condensate and Gases Formed in Combustion of Model Wood Volatile Compounds," paper presented at the International Conference on Fundamentals of Thermochemical Biomass Conversion, Estes Park, Colorado, October 18-22, 1982.

100. Tillman, David A. "Review of Mechanisms Associated with Wood Combustion," Wood Science, Vol. 13, No. 4, April 1981, pp. 177-184.

Relationships between operational parameters and physical conditions occurring in the combustion process are discussed. For example, the effect moisture content has on the energy requirement to heat fuel particles to pyrolysis temperature is investigated.

101. U.S. Department of Energy, Bonneville Power Administration. "Utility in Bid to Cut Price for Cogenerator Energy," Bioenergy Bulletin, Vol. 5, No. 4, October 1984, p. 3.

102. Walawender, Water P. "Technical Evaluation of the Buck Rogers Gasifier," project report submitted to the Buck Rogers Company, Inc., Industrial Airport, Kansas, 1983.

103. White, E.W. and M.J. Thomson. "The Enerco Pyrolysis System," Chaper 20 in Thermal Conversion of Solid Wastes and Biomass edited by Jones and Radding, Washington, D.C.: American Chemical Society, ACS Symposium Series 130, 1980, pp. 275-283.

104. Williams, R.O., et al. "Development of Pilot Plant Gasification Systems for the Conversion of Crop and Wood Residues to Thermal and Electrical Energy," paper appearing in Solid Wastes and Residues - Conversion by Advanced Thermal Processes edited by Jerry L. Jones and Shirley B. Radding, American Chemical Society, ACS Symposium Series 76, Washington, D.C., 1978, pp. 142-162.

Gasification research being conducted at U. of California, Davis, is reviewed. A down draft, moving, packed bed, vertical flow gasifier is the basis for most of this research. Gasified design, gasification rate and process variables are discussed, and specific applications and cost projections are presented.

105. Wilson, H.T. and J.R. Gibbins. "Biomass Gasification Developments," paper presented at Biomass to MeOH Specialist's Workshop, Tammaran, Colorado, March 3-5, 1982.

106. Yonaka, Kenneth and Peter Schiess. "Evaluation of The Whole Tree Baler in the Pacific Northwest," paper #PNR-82-502 presented at regional meeting of American Society of Agricultural Engineers, Oregon State U., Corvallis, Oregon, September 17, 1982. This paper was reviewed in Bioenergy Bulletin, Vol. IV No. 2, published by U.S. Dept. of Energy, February 1983, pp. 4-5.104.

107. Zink, H.R., S.L. Bozdech and J.C. Popp. "Seed Corn Drying with Cob Gasification," paper presented at the 1982 Winter Meeting of the American Society of Agricultural Engineers, Chicago, Illinois, December 14-17, 1982.

The DeKalb-Pfizer Genetics gasifier system and its application to drying corn is discussed. It is an updraft airblown unit that uses corn cobs for fuel. It is a simple, automatic system that largely has met its original design objectives.

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PROJECT EXPENSE SUMMARY - CONTRACT ED-LJW-650
(Details in Attachments)

	Contractor Portion		DNRC Portion		Combined	
Salary Expenses						
Milestone 1	$742.58		$742.58		$1485.11	
" 2	985.04		755.00		1740.04	
" 3	2467.50		2070.00		4537.50	
" 4,5	8557.50		4011.42		12,452.50	
" 6	2675.00		2200.00		4875.00	
Total		$15,427.62		9779.00		$25,206.62
Contracted Services						
Milestone 4,5	114.37		945.00		1059.37	
" 6	208.00		—		208.00	
Total		322.37		945.00		1,267.37
Travel Expenses						
Milestone 2	196.00		116.00		312.00	
" 4,5	598.00		—		598.00	
Total		794.00		116.00		910.00
Office Supplies						
Milestone 1	10.00		—		10.00	
" 2	15.00		—		15.00	
" 4,5	10.00		—		10.00	
" 6	50.00		—		50.00	
Total		85.00				85.00
Telephone						
Milestone 1	200.00		—		200.00	
" 2	10.00		—		10.00	
" 4,5	150.00		—		150.00	
" 6	15.00		—		15.00	
Total		375.00				375.00
Printing & Reproduction						
Milestone 1	20.00		—		20.00	
" 2	80.00		—		80.00	
" 4,5	85.00		—		85.00	
" 6	140.00		—		140.00	
Total		325.00				325.00
Postage						
Milestone 1	20.00		—		20.00	
" 2	5.00		—		5.00	
" 4,5	8.00		—		8.00	
" 6	4.15		—		4.15	
Total		37.15				37.15
Rental & Utilities		890.00	—			890.00
Total, Contractor Portion		$18,256.14				
Total, DNRC Portion				$10,840.00		
Total, Combined						$29,096.14

I certify this summary is correct — Laurence J. Katz

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